Classic Paper in the History of Geology

Inge Lehmann's paper: " P' " (1936)

"We take it that, as before, the Earth consists of a core and a mantle, but that inside the core there is an inner core in which the velocity is larger than in the outer one." — Lehmann (1936).

In 1936, the Danish seismologist Inge Lehmann (1888–1993), who worked for the Danish Geodetic Institute from 1925 to 1952, suggested from the analysis of P-wave data that the Earth must have an inner core — an important breakthrough in the understanding of the nature of the Earth's interior.

Inge Lehmann (1888–1993)

Inge Lehmann (Figure 1) was born on 13 May, 1888, near Copenhagen, Denmark, one of two daughters of Alfred Lehmann, a professor of psychology at the University of Copenhagen, and his wife. The child was sent to a small private school run by Hannah Adler, an aunt of physicist Niels Bohr. This school was co-educational, a feature that was rather unusual for the time (Bolt, 1997). As Lehmann later recollected, boys and girls were treated alike: "[n]o difference between the intellect of boys and girls was recognised, a fact that brought some disappointment [to me] later in life when I had to recognise that this was not the general attitude" (quoted after Brush, 1980). She had, for example, to reach the age of 27 before she could take part in her first political election, since the right to vote was not granted to women in Denmark before 1915 (Bundesministerium für Frauen und Jugend, 1993).

In 1907, Lehmann entered the University of Copenhagen to study mathematics, and also attended courses in physics, chemistry, and astronomy. (Women had been admitted to Danish universities from 1875 onwards [Rupp, 1978].) She took the first part of the required examinations in 1910 and then continued her studies at Newnham College, Cambridge (U.K.), where she experienced "the severe restrictions inflicted on the conduct of young girls, restrictions completely foreign to a girl who had moved freely amongst boys and young men at home" (quoted after Bolt, 1997). Newnham College was one of two women's colleges in Cambridge at that time, but though allowed to attend university lectures and sit the examinations women were not admitted to university degrees before 1948 (Alic, 1986). In December, 1911, Lehmann became seriously ill through overwork and was forced to return home, where she worked for some years as a 'computer' or calculator in an actuary's office. In 1918, she resumed her university training as mathematician at The University of Copenhagen and graduated in the summer of 1920. From February, 1923 onwards, she worked as assistant to the professor in actuarial sciences. In 1925, she became assistant to Professor N.E. Nörlund, Director of the geodetic institution *Den Danske Gradmaaling* (Bolt, 1997).

Nörlund had become interested in establishing seismic stations in Denmark and Greenland, and the best available seismographs were used for the new stations (Lehmann, 1987). "I began to do seismic work and had some extremely interesting years in which I and three young men who had never seen a seismograph before were active installing Wiechert, Galitzin-Wilip and Milne-Shaw seismographs in Copenhagen and also helping to prepare the Greenland installations. I studied seismology at the same time unaided …" (quoted after Bolt, 1997). It was around that time that Lehmann "heard for the first time that knowledge of the Earth's interior composition could be obtained from the observations of the seismographs. I was strongly interested in this and started reading about it" (Lehmann, 1987). In the summer of 1927, Lehmann received the opportunity to visit some notable European seismic stations: "I was sent abroad for three months. I spent one month with Professor Beno Gutenberg in Darmstadt [Germany]. He gave me a great deal of his time and invaluable help." (quoted after Bolt, 1997). She also paid short visits to Hamburg (Germany), Strasbourg (France), De Bilt (The Netherlands) and Uccle (Belgium) (Bolt, 1997).

Figure 1 Inge Lehmann. Photograph reproduced from Brush (1980, Fig. 9)

In the summer of 1928, Lehmann obtained a master's degree in geodesy from The University of Copenhagen, submitting a thesis on a seismological topic. The same year, she was appointed chief of the seismological department of the new geodetic institute, a post that she held until her retirement in 1953. Her task was to keep the instruments in Copenhagen well adjusted and to instruct the staff of the remote Greenland stations. She interpreted the institute's seismograms and published the bulletins of the seismic stations. Most of the time, she did not have assistants, not even for office work. Original scientific research was not regarded as part of her duties, but she was free to pursue it, if she liked, and she published thirty-five papers during the period of her appointment. Apart from her interest in the travel-time curves of the various types of seismic waves, which in 1936 led her to suggest the existence of an inner core for the Earth, she made determinations on the reliability of seismic stations in Europe and discussed how to obtain meaningful observations. She also worked on small local earthquakes and on microseismic wave motions generated by storms over the Arctic and North Sea (Bolt, 1997).

In 1936, Lehmann was one of the founders of the Danish Geophysical Society, and in 1941 and 1944 she chaired the organisation (Bolt & Hjortenberg, 1994). (It was, it may be noted, the time of World War II, and male applicants for the position had become scarce.)

Lehmann's career was before the era when electronic computers became available, so her organisation of data and computations was done 'by hand':

> *"I remember Inge one Sunday in her beloved garden on Sobakkevej; it was in the summer and she sat in the lawn with a big table filled with cardboard oatmeal boxes. In the boxes were cardboard cards with information on earthquakes and the times for these and times for their registration all over the world. This was before computer processing was available, but the system was the same. With her cardboard cards and her oatmeal boxes, Inge registered the velocity of propagation of the earthquakes to all parts of the globe. By means of this information, she deduced new theories of the inner parts of the Earth."* (Nils Groes, a relative of Inge Lehmann, quoted by Bolt & Hjortenberg, 1994).

This method, without the help of assistants, was burdensome, but had the advantage that Lehmann personally saw and interpreted the seismograms, paying attention not only to arrival times but also to other (more descriptive) characteristics of the seismic waves, such as their relative amplitudes and 'shapes'. How this seemingly primitive method helped with the discovery, e.g., of the inner core of the Earth becomes apparent in the second part of Lehmann's 'classic paper', *P*' (Lehmann, 1936; see below).

It was not easy for a woman to gain entry to the mathematical and scientific establishment in the first half of the twentieth century. As Lehmann said: "[y]ou should know how many incompetent men I had to compete with — in vain" (Groes, in Bolt & Hjortenberg, 1994). Lehmann tried to compensate for the disadvantages caused by prejudice against her gender by hard work. "Inge's grown-up life was characterised by hard work, tough grind, a magnificent scientific effort, and, finally, great academic appreciation." (Groes, in Bolt & Hjortenberg, 1994). Like most female scientists of her day, she never married. To have done so would almost certainly have meant the end of her scientific career.

After her retirement in 1953, and when relieved from routine duties, Lehmann entered a second, fruitful research phase, working on the structure of the upper Earth's mantle and its seismic discontinuities. She frequently visited seismic observatories in the USA and Canada. It was in this late phase of her career that she started to receive international recognition in the form of numerous awards for her work and for her exceptional expertise in observing and interpreting seismological raw data. "The Lehmann discontinuity [the core/inner core boundary] was discovered through exacting scrutiny of seismic records by a master of a black art for which no amount of computerisation is likely to be a complete substitute", said Francis Birch at the occasion of the awarding of the Bowie Medal of the American Geophysical Union in 1971. Recognition in Denmark took some time: in 1968, she received an honorary PhD from the University of Copenhagen in her 80th year (Bolt, 1997).

Here follow extracts from Lehmann's classic paper of 1936, with explanatory interpolations in italics. The original page numbering is given in parentheses.

Inge Lehmann (1936): P'

[*p. 87 of the original paper*]

I

P' Time-Curves

P is used to denote longitudinal or 'pressure' seismic waves. Those that travel in the Earth's mantle and crust only are represented by P; P' represents P-waves that pass through the mantle into the core, and then pass through the mantle again.

1. The retardation observed in longitudinal waves at great epicentral distances is explained by the assumption of a decrease in their velocity in the interior of the earth. The course of the time-curve agrees roughly with a sudden fall in the velocity at a depth of about 2900 km.

This sudden decrease in velocity occurs as the wave crosses the core-mantle boundary. Seismic waves propagating through the deep interior of the Earth arrive significantly later than would be expected if the globe were homogeneous. They are retarded by the fluid core, where seismic waves pass more slowly than through the mantle.

For the purpose of illustrating the characteristics of the *P* and *P*' curves we have adopted the simple assumption of constant velocity of 10 km/sec in the mantle and of 8 km/sec in the core. The radius of the core is taken to be 5/9 r_0; r_0 = 6370 km, being the radius of the earth.

This is a simplified assumption, since in reality the velocity in the mantle (and again within the core) increases with depth more or less uniformly, due to the increasing density caused by the increasing pressure. There are also some smaller discontinuities within the Earth's upper mantle, some of which were already known when Lehmann wrote her paper. This simplification of the problem, omitting unnecessary detail and complications, was seen as Lehmann's strength and later helped to gain recognition and acceptance of her idea.

In Figure [*2a = Fig. 1 in the original Lehmann paper*] a ray passing only through the mantle has been drawn from the epicentre E to point 1 on the surface. …

Rays are lines drawn perpendicularly to the propagating wave-front. Lehmann now calculates and explains what paths are to be expected for her simplified model of an Earth with a homogeneous mantle and core. For the purpose of our summarised version of Lehmann's paper we omit the mathematics and only follow her graphical reasoning. Figure 2a of the present paper is not Lehmann's original figure but a re-drawn version to make things clearer for non-specialist readers. In Lehmann's simplified Earth model, the rays of the P-waves are straight lines. In reality, the rays in the mantle curve upwards, as shown in the inset to Figure 2b.

[*p. 88*]
The angle of incidence [,] i_0 [,] of the ray which meets the core at grazing incidence is 33°.75 [*(or 33.75°)*]. … The corresponding rays E 2 and E 2a have been drawn in the figure as well as the rays E 3 and E 4, penetrating the core. …

The ray with an angle of incidence of 33°.75 just meets the boundary of the core. The ray is split into two parts, one which proceeds straight through the mantle to reach the surface at Point 2, and one that penetrates the core and is refracted at the boundary because of the different velocities in the two media. It reaches the surface again at Point 2a. Since seismic waves travel in the core with lower velocity than in the mantle, the Earth's core operates as a crude converging lens for seismic waves. It depends on the angle of incidence, how much any given ray is deflected at the core-mantle boundary. The smaller the angle of incidence, the less the ray is refracted.

[*p. 90*]
The *P* … [*rays break*] off at Δ = 112°.5 [*i.e., Point 2. Δ = the angular distance from the epicentre to the point, where a ray again meets the surface, given in degrees (see Figure 2a).*], corresponding to i_0 = 33°.75. For this angle of incidence we have also Δ = 186°.2 [*i.e. Point 2a*]. ...

For i_0 decreasing from 33°.75 to about 26°… [*P'_2 rays are generated*] in the direction indicated by the [*dashed*] arrow; … [*they end*] at an epicentral distance of 153°.9. When i_0 decreases from 26°, … [*P'_1 rays are*] generated … [*running*] forward to Δ = 180° [*dotted arrow*].

Thus a shadow zone, between 112°.5 and 153°.9 is generated in which no evidence of the earthquake should be detected.

Having shown how a seismic wave passes through her simplified model of the Earth, Lehmann now proceeds to calculate the amount of energy that a given surface area receives from the shock. From this, she infers the expected amplitude of the individual ray arriving at an individual seismograph.

2. The energy contained in a small bundle of rays is proportional to the surface element. … Where the bundle of rays again meets the surface of the earth it cuts out the surface element …

Lehmann gives the formulae according to which the intensity of the ray, i.e. the transmitted energy as a function of the angle of incidence can be calculated.

[*p. 92*]
It is hereby assumed that no energy is lost on the way whereas in reality energy is lost, especially at discontinuity surfaces, where part of the energy is reflected and part of it possibly refracted into a wave of different kind [*e.g. P- into S- waves*]. For our purpose, however, the simple … [*formula, just developed*] is all that is needed.

3. …

Through mathematical reasoning, Lehmann points out that the energy transmitted by the P'_2 rays is difficult to estimate:

The energy of the corresponding ray, however, is not necessarily insignificant, for $\sin\Delta$ is quite small while $\tan i_0$ assumes greater values. This simply relates to the fact that energy originally sent out in different directions concentrates on a small area.

Conclusions as to the energy of P'_2 therefore cannot be drawn without further examination; but close to the cusp at which P'_2 turns into P'_1 [*i.e. at epicentral distance, Δ, close to 153°.9, at the very edge of the shadow zone*] the energy is great. … There is thus a focal zone in which the P' amplitudes are very large; P'_1 and P'_2 both [*p. 93*] occur and the energy of both is great. They are quite close together, so close that it might not be possible to separate their pulses on a record.

4. The velocity distribution here assumed is simpler than the one actually found in the Earth. The [*calculated*] P' curves therefore deviate from those empirically determined; their slopes and the critical distances are different. But, on the simpler assumption, both the P'_2 and P'_1 phases occur, and there is a focal zone where the energy of the ray is great. So far there is agreement with actual observations.

5. There are however observations which are not immediately explained on the assumption made here, nor do they find any explanation if gradually increasing velocity is assumed instead of constant velocity [*i.e., they are not a fault of the simplified model*], or if the discontinuity surfaces in the upper part of the mantle are considered. It is actually found that the P curve does not break off abruptly [*as it should as Lehmann has shown*], but continues in a curve corresponding to a ray of small intensity; it is also found that P' is not confined to distances greater than the focal distance of about 143° [*i.e. the upper limit of the shadow zone in the real Earth, with curved seismic rays*] but is observed, though with smaller amplitudes, at smaller distances down to about 105°.

Diffraction has been resorted to for want of an explanation of the small P beyond about 100° as well as the small P' at distances smaller than the focal distance. At the discontinuity surface which separates mantle and core the entire energy would not be carried by refracted and reflected waves, put part of it would be spread in other waves carrying but a small amount of energy to the surface.

6. The P waves observed at distances greater than about 100° are always quite small and only recorded by the most sensitive instruments so that for a long time it was believed that they are not present at all.

This is why a shadow zone was initially discovered, which led to the postulation of an Earth core, with lower seismic velocities than in the mantle. For discussions of the history of researches on the Earth's core, see Brush (1980) and Bolt (1987).

Diffraction may afford an acceptable explanation of the [*p. 94*] occur[*r*]ence of these waves, but it is not the only possible explanation.

…

Lehmann then shows by calculation that the occurrence of P-waves within the shadow zone could also be explained by the assumption of a layer of gradual decreasing P' wave velocity on top of the sudden velocity drop at the core-mantle boundary.

[*p. 95*]
7. The view has previously been held that the P' waves reaching the surface at distances smaller than the focal distance (hereafter, for simplicity, to be denoted P'_3) were small and insignificant. This has been found not to be so. The horizontal component of the movement is indeed small, but the vertical component may be considerable, and evidently the lack of vertical component instruments has caused the false impression to be gained of P'_3 being quite small.

In a study of the P' records of the Buller earthquake of 1929 June 16 [*New Zealand, Magnitude 7.7, according to the USGS*] I have drawn attention to the fact that P'_3 might be a strong wave and that the amplitude increased with increasing distance. …

Later, other observers have also found that P'_3 might be of considerable amplitude.

…

Lehmann gives several examples.

[*p. 97*]
8. An explanation of the P'_3 wave is required, since now it can hardly be considered probable that it is due to diffraction.

Otherwise, different characteristics from those explained in Paragraph 7 would be expected.

A hypothesis will here be suggested which seems to hold some probability, although it cannot be proved from the data at hand.

We take it that, as before, the earth consists of a core and a mantle, but that inside the core there is an inner core in which the velocity is larger than in the outer one. The radius of the inner core is taken to be $r_1 = 8/10\ r_0 \sin 16° = 0.2205\ r_0$, so that the ray whose angle of incidence at the surface of the Earth is 16° just touches the inner core.

…

Lehmann again assumes a constant velocity for seismic waves within the inner core of 8.6 km/sec, this being faster than that within the outer core. Thus, the inner core functions as a crude dispersing lens for seismic waves.

[*p. 98*]
9. The P'_2 … [*rays in Figure 2b are like those in Figure 2a*]. As before … [*they join the P'_1 rays, running forward again*]. But [*these rays break*] off at Δ = 160°.7 corresponding to i_0 = 16°.

This is the largest angle of incidence at which a ray meets the inner core of Lehmann's model Earth.

[*F*]or i_0 = 14°.85 … [*, the ray hitting the boundary of the inner core is totally reflected. It reaches the surface of the Earth*] at Δ = 118°.8. At this point it is joined … [*by*] the ray[*s*] which … [*pass*] through the inner core; for values of i_0 decreasing from 14°.85 to 0° it runs forward to Δ = 180°. …

The … [*ray of total reflection is*] of quite small intensity. …

[*p. 100*]
But the intensity of the P'_3 ray increases with increasing distance. … It is thus seen that, even at distances smaller than the focal distance [*i.e. within the shadow-zone of Figure 2a*] … the intensity of the ray

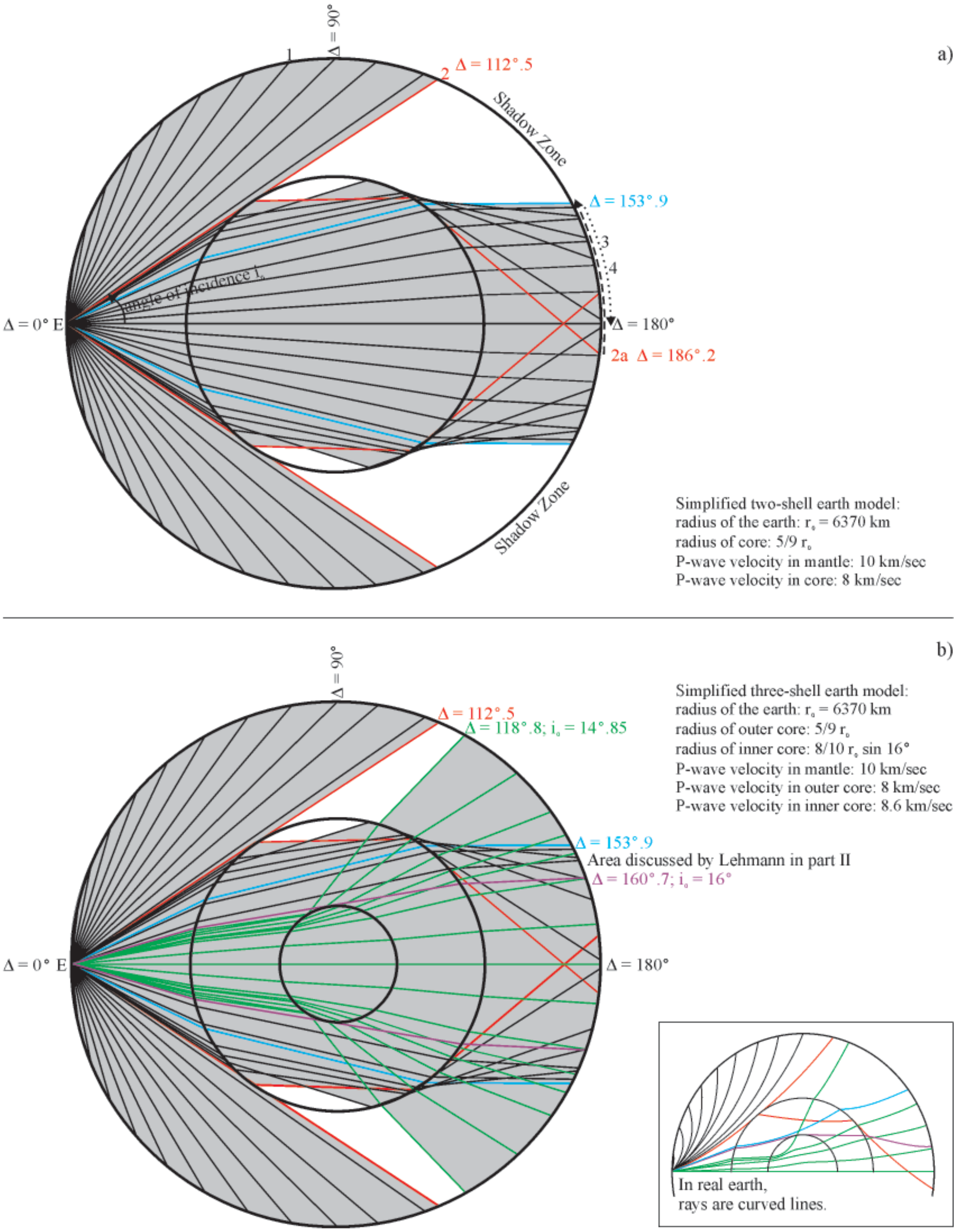

***Figure 2** a) Seismic P waves from an earthquake passing through Lehmann's simplified two-shell Earth model. Data from Lehmann (1936) have been used in preparing the drawing. For further explanation, see the text of the present paper. E = epicentre. The red rays meet the core at the grazing angle. The blue rays indicate the critical angle of incidence, corresponding to the far boundary of the shadow-zone.*

b) Seismic P waves from an earthquake passing through Lehmann's simplified three-shell Earth model. Data from Lehmann (1936) have been used for the drawing. E = epicentre. The red and blue rays are the same as above. The purple rays meet the inner core at grazing angle; green rays pass through the inner core. For further explanation, see the text of the present paper.

Inset: this shows, for purposes of comparison, curved rays passing through the real Earth, represented according to modern views. Re-drawn after Strobach (1983).

is not quite small. The angle of incidence being small, the vertical component of the movement is relatively large.

These characteristics of P'_3 are the same as those actually observed.

10. …

Lehmann discusses details of interpretation compared to data by other seismologists such as Gutenberg, Richter, or Jeffreys.

[*p. 101*]
11. … We have taken the increase of velocity to occur abruptly at the boundary of the inner core, but time-curves similar to those here considered may result if, instead of a discontinuous increase, a gradual, but very strong increase of velocity is assumed.

[*p. 102*]
12. …

Lehmann repeats her reasoning for S-waves and shows that data for this wave-type is also consistent with her model of an Earth with an inner core.

Although the outer core is fluid and thus not able to propagate S-waves (transverse waves), part of their energy is converted at the core-mantle boundary into P-waves, which are able to traverse the Earth's core. Thus, there is a (weak) signal of S-waves on the far side of the core.

[*p. 105*]

II

P' Record of the Buller Earthquake

This part of Lehmann's paper gives some insight into her methodology.

1. It will hardly be possible to determine with much certainty the time-curves of the P' phases around the focal distance unless detailed studies are made of earthquakes recorded by a group of stations at this distance. The phases are close together and therefore are not easily separated except by direct comparison of records of stations within a small range of distance.

That is, the stations are to be used as an 'array' to filter out background noise more effectively, thus increasing the sensitivity of the measurements.

Records of a group of stations in the focal zone have not been available, but the Buller (New Zealand) earthquake of 1929, June 16, previously studied [*Lehmann, 1930*], gave four P' records at distances around 150°. In the earlier investigation the first pulse only was considered in these four records, since it did not seem possible to interpret the later pulses. P'_2 was read at greater distances and was obviously present also at 150°, but it did not seem certain which of the later pulses were due to P'_2 and therefore no readings of this phase were [*p. 106*] given. The records have now been studied in detail and interpretation attempted.

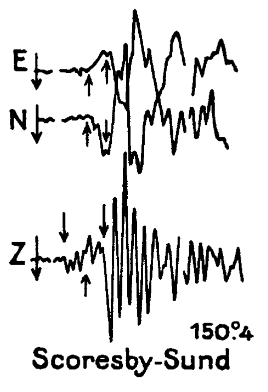

Figure 3 Scoresby-Sound P' records of the Buller earthquake, New Zealand (Lehmann, 1936, Fig. 6). The seismographs Lehmann used gave records of the Earth movements in three directions. E represents the East-West wave component. N represents the North-South wave component. Z represents the vertical wave component.

The four stations are Ivigtut (149°.0), Abisco (149.9°), Scoresby-S[*o*]und (150.4°) and Pulkovo (150.6°). They are not in a group, but at great distances from each other. Their records, however, have common features.

The Scoresby-S[*o*]und P' records have been reproduced in Figure [*3 = Fig. 6 in the original Lehmann paper. E represents the East-West wave components, N represents the North-South wave components, Z represents the vertical wave component.*] The beginning is quite small and is barely visible on the original Z record (not on the reproduction); there is an increase on Z where movement begins on N and E; later there is a simultaneous increase of movement on all component records; finally large oscillations set in on Z; there is a simultaneous increase of movement on N and E, but the separation of phases is not very clear.

In the records of the other stations the movement increases in a similar way. The large oscillations are in all cases much larger than those of P'_1 and P'_2 at greater distances.

…

Lehmann gives a table of the readings she has obtained and discusses briefly the quality of the data. She also gives a plot of her data-points together with transmission times from other stations, not reproduced here. The following paragraph refers to this data plot.

[*p. 108*]
The fact that the points [*of the stations*] near 150° are on four lines may be taken as an indication of the existence of four distinct waves, even though some of the points are not due to very definite pulses in the records. …

2. If there is no discontinuity within the core we should at 150° have barely two P' phases, P'_1 and P'_2, with a short interval between them, neither of them weaker than at greater distances. If there is an inner core the first phase P'_1 may be weaker than at greater distances. It should possibly be followed by a second, stronger P'_1 phase and there should, in any case, be a P'_2 phase, probably rather strong.

The observed construction of the P' phase at 150° does not seem to be in accordance with either of these possibilities. There are four phases instead of 2 or 3.

3. The first phase however is quite weak. In the earlier [*p. 109*] paper [*Lehmann, 1930*] it was mentioned that the P' record of Köbenhavn [*Copenhagen*] as well as of other stations was introduced by quite a small vertical movement; the following movement had rather a strong vertical component and was also recorded by horizontal component instruments. A small introductory movement therefore is nothing special for distances around 150°.

This small first movement may have been caused by one or more small shocks immediately preceding the main shock.

…

Lehmann discusses this possibility, in view of data obtained closer to the earthquake's epicentre. She concludes that:

[*p. 110*]
… though the data are insufficient and a clear distinction between $P's$ due to different shocks is not possible, there is little doubt that smaller shocks precede the main disturbance.

4. The small introductory movement observed in P' at distances between 160° and 170° as well as at about 150° is likely to be due to these smaller shocks. Since in my previous paper [*Lehmann, 1930*] the readings headed P'_1Z are readings of the first faint beginning of the phase, they are related to the foreshocks. These on the other hand are hardly recorded on the horizontal component instruments where the P'_1 movement is weak throughout, so that the readings headed

P'_1H are likely to be due to the main shock. The corresponding points do not give a satisfactory determination of a [*transmission times*] curve, but this is not surprising since the weak and indefinite beginning of the phase cannot be equally well recorded by instruments of varying sensitivity.

An attempt was therefore made to determine the P'_1 curve of the main shock from the vertical component records. On all of them increase of movement takes place shortly after the faint beginning of the phase and the setting in of the stronger movement is likely to be due to the arrival of the P'_1 wave of the main shock.

…

Lehmann proceeds to discuss the construction of a travel-times curve for P'_1, using data from stations in Europe and Siberia and deploying the method she suggested above.

[*p. 113*]

6. Either the third or the fourth set of pulses found in the records at distances of about 150° is likely to mark the arrival of P'_2 which should be stronger here than at greater distances.

…

[*p. 114*]

Lehmann shows that the fourth set should be due to P'_2.

The corresponding phases are less clearly indicated in the records than any of the other P' phases read; however, the movement following upon the third pulse is in all cases so very large and continues so long that it is more probably due to two waves than to only one. We cannot expect a great concentration of energy in either P'_1 or P'_2 at such great distance from the focal point.

…

7. We may summarise as follows: In four records at distances of about 150° pulses have been read which seem to indicate that there are four distinct P' waves at this distance. The first, small wave, recorded on vertical component instruments only, is likely to be due to small shocks preceding the main shock. The second wave which is not very large has been interpreted as the P'_1 wave of the main shock, recorded also at greater distances. At smaller distances the same wave is recorded as P'_3. The movement arising from the third and fourth waves is very large. The phases have [*p. 115*] been interpreted as the upper P'_1 and the P'_2 phases. This interpretation presupposes the existence of an inner core.

It cannot be maintained that the interpretation here given is correct since the data are quite insufficient and complications arise from the fact that small shocks have occurred immediately before the main shock. However, the interpretation seems possible, and the assumption of the existence of an inner core is, at least, not contradicted by the observations; these are, perhaps, more easily explained on this assumption.

8 I hope that the suggestions here made may be considered by other investigators, and that suitable material may be found for studies of the P' curves. The question of the existence of the inner core cannot however be regarded solely from a seismological point of view, but must be considered also in its other geophysical aspects.

Two years later, Gutenberg and Richter calculated from available travel-time data an inner core radius of about 1,200 km and a mean inner core P velocity of 11.2 km/sec. In 1939, Harold Jeffreys showed that the older interpretation of P'_3 phases as diffracted waves was untenable, supporting thus Lehmann's three shells model. The rate of velocity increase at the boundary of the inner core remained controversial for about twenty years, when a true discontinuity was finally accepted. That the inner core was solid, as opposed to the fluid outer core, was proposed independently by Birch in 1940 and by Bullen in 1946 (Bolt, 1997).

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Martina Kölbl-Ebert
Bayerische Staatssammlung für Paläontologie und Geologie
Funktionseinheit Geologie
Luisenstrasse 37
80333 München (Munich)
GERMANY
E-mail: martina.koelbl@iaag.geo.uni-muenchen.de